The NASA Orbiting Carbon Observatory (OCO) Mission: Objectives, Approach, and Status

Thomas R. Livermore and David Crisp
Jet Propulsion Laboratory/California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109
818-354-1118
Thomas.R.Livermore@JPL.NASA.GOV

Abstract— The Orbiting Carbon Observatory (OCO) is a NASA Earth System Science Pathfinder (ESSP) mission that is currently under development at the Jet Propulsion Laboratory (JPL). OCO will make global, space-based measurements of atmospheric carbon dioxide (CO_2) with the precision, resolution, and coverage needed to characterize regional-scale sources and sinks of this important greenhouse gas. The observatory consists of a dedicated spacecraft bus that carries a single instrument. The bus employs single-string version of Orbital Sciences Corporation (OSC) LEOStar-2 architecture. This 3-axis stabilized bus includes a propulsion system for orbit insertion and maintenance, provides power, points the instrument, receives and processes commands from the ground, and records, stores, and downlinks science and engineering data. The OCO instrument incorporates 3 co-boresighted, high resolution grating spectrometers that will make coincident measurements of reflected sunlight in near-infrared CO_2 and molecular oxygen (O_2) bands. The instrument was designed and manufactured by Hamilton Sundstrand (Pomona, CA), and then integrated, flight qualified, and calibrated by JPL. It is scheduled for delivery to OSC (Dulles, VA) for integration with the spacecraft bus in the spring of 2008. OCO will be launched from the Vandenberg Air Force Base on a dedicated OSC Taurus XL launch vehicle in December 2008. It will fly in formation with the Earth Observing System Afternoon Constellation, a group of satellites that files in a 98.8 minute, 705 km altitude, sun-synchronous orbit. This orbit provides coverage of the sunlit hemisphere with a 16-day ground track repeat cycle. OCO will fly ~4 minutes ahead of the EOS Aqua platform, with an ascending nodal crossing time of ~1:26 PM. The OCO science data will be transmitted to the NASA Ground Network Stations in Alaska and Virginia, and then transferred to the OCO Ground Data System at JPL. There, the CO_2 and O_2 spectra will be analyzed by the OCO Science Team to provide spatially resolved estimates of the column-averaged CO_2 dry air mole fraction, X_{CO2}. These measurements are expected to improve our understanding of the nature and processes that regulate atmospheric CO_2 enabling more reliable forecasts of CO_2 buildup and its impact on climate change.

TABLE OF CONTENTS

1. INTRODUCTION

Carbon dioxide (CO_2) is produced every time we light a fire, start a motor or exhale. Rapid increases in the concentration of this gas are raising concerns because CO_2 is an efficient greenhouse gas, which traps thermal radiation and contributes to global warming. Precise ground-based measurements of CO_2 made since the late 1950's indicate that the atmospheric CO_2 volume mixing ratio has increased from ~310 to over 380 parts per million (ppm) over this period. Comparisons of these data with estimates of CO_2 emission rates from fossil fuel combustion, biomass burning, and other human activities indicate that only about half of the CO_2 that has been emitted into the atmosphere over the past half century has remained there. The rest has apparently been absorbed by surface "sinks" in the land biosphere or oceans. Existing CO_2 measurements also show that the atmospheric CO_2 buildup varies dramatically from year to year in response to smoothly increasing emission rates. The existing CO_2 monitoring network does not have the spatial resolution, coverage, or sampling rates needed to identify the natural CO_2 sinks or the processes that control how their efficiency variations over time. An improved understanding of the processes that are controlling the present-day atmospheric CO_2 are essential for predicting the rate of CO_2 increases and their impact on the climate.

To address these issues, NASA selected the Orbiting Carbon Observatory (OCO) as the fifth mission in Earth System Science Pathfinder (ESSP) Program. The ESSP Program uses competitively selected, low cost Earth science missions, to make highly focused exploratory measurements of the Earth system to improve our ability to predict changes in weather, climate, and natural hazards. During its nominal two-year operational lifetime, OCO will make space-based measurements of CO_2 and molecular oxygen (O_2) over the sunlit hemisphere of the Earth. These data will be analyzed with remote sensing algorithms to retrieve estimates of the column-averaged CO_2 dry air mole fraction, X_{CO2} with the accuracy and sampling resolution needed to characterize surface sources and sinks of CO_2 on regional scales over the entire globe. This paper provides a brief overview of the mission design and implementation approach and provides an update on the development status.

2. Measurements Needed

Carbon cycle studies [1] indicate that our understanding of sources and sinks of CO_2 could be substantially improved by augmenting the data from the ground-based CO_2 monitoring network with high spatial resolution, global, space-based CO_2 measurements. While measurements of near-surface CO_2 profiles would provide the greatest value, spatially resolved estimates of the column-averaged CO_2 dry air mole fraction, X_{CO2}, could yield dramatic improvements if they provide adequate precision and spatial sampling. High precision is essential for this application because source-sink inversion models infer surface-atmosphere fluxes of CO_2 from spatial and temporal variations in X_{CO2}, and this quantity is expected to vary by no more than ~2% on regional to global scales [2]. These modeling studies indicate that regional scale X_{CO2} measurements with precisions near 0.3 to 0.5 % (~1 to 2 parts–per million (ppm) out of the ambient ~380 ppm CO_2 mixing ratio) would reduce existing uncertainties in surface CO_2 fluxes by up to 80% over much of the globe [3,4]. Global measurements are needed at monthly intervals characterize the variability of sources and sinks over the seasonal cycle. While a one-year mission duration of one year could capture the behavior of sources and sinks over a single seasonal cycle, a longer mission is needed to discriminate the relative roles of rainfall, and other factors that affect CO_2 absorption by land plants and other natural sinks from year to year.

3. Mission Design

To provide near complete coverage of the sunlit hemisphere, the Observatory will be launched into a 98.2° inclination, sun-synchronous orbit from Vandenberg Air Force Base in California, on a dedicated Orbital Sciences Taurus XL (3110) launch vehicle. The target launch date is December 2008. The observatory will initially be launched into a 640±30 km transfer orbit. Once the spacecraft bus has been checked out, the orbit will be raised to 705 km altitude, to fly in formation with the Earth Observing System (EOS) Afternoon Constellation (A-Train). OCO will fly ~4 minutes ahead of the EOS Aqua platform, with an ascending nodal crossing time of 1:26 PM, such that it shares the same ground track as Aqua. [5]

Flying in the A-Train facilitates comparisons of OCO observations with other environmental measurements collected by instruments on Aqua and other A-Train satellites (Aura, CloudSat, and CALIPSO). This orbit's ground track repeats every 16 days, providing complete coverage of the sunlit hemisphere at semi-monthly intervals. The orbit's 98.7 minute period yields 14.56 orbits per day. Successive orbit tracks are separated by ~24.6° of longitude (~2700 km at the equator). After 16 days, the 233 orbits included in each ground-track repeat cycle have a mean longitude spacing of ~1.5° (~170 km at the equator). A sun-synchronous orbit was advantageous because it samples the entire sunlit hemisphere at same time of day, minimizing uncertainties associated with the CO_2 diurnal cycle. This early afternoon sampling time is nearly ideal for spectroscopic observations of CO_2 in reflected sunlight because the sun is high, maximizing the measurement signal-to-noise ratio.

The observatory carries a single instrument that measures the absorption of reflected sunlight by CO_2 and molecular oxygen (O_2) at near infrared wavelengths. High spectral resolution ($\lambda/\Delta\lambda$>20,000) measurements within the CO_2 bands near 1.61 and 2.06 μm yield CO_2 column abundance estimates that are most sensitive to the CO_2 concentrations near the Earth's surface. High resolution ($\lambda/\Delta\lambda$>17,000) measurements within the 0.765-μm O_2 A-band spectra yield clear-sky surface pressure estimates with accuracies near 1 mbar and constrain cloud and aerosol profiles to reduce optical path length uncertainties associated with multiple scattering. Co-boresighted measurements of the CO_2 and O_2 spectra will be analyzed to retrieve spatial variations in the column-averaged CO_2 dry air mole fraction, X_{CO2}.

The space-based X_{CO2} measurements will be validated against *in situ* and remote sensing data from a ground-based network to ensure that the space-based X_{CO2} measurements have precisions of 0.3% (1-ppm CO_2) on regional scales at monthly intervals. Once validated, these measurements will be incorporated into sophisticated source-sink inversion models to characterize the geographic distribution of CO_2 sources and sinks over two annual cycles.

4. Implementation Approach

Spacecraft Bus

OCO uses a dedicated spacecraft bus based on the single-string version of Orbital Sciences LEOStar-2 architecture.[5] This 3-axis stabilized bus supports the instrument through launch and orbit insertion, provides power, points the instrument, receives and processes commands from the ground, and records, stores, and downlinks the data collected by the instrument. The instrument is enclosed within the upper half of the bus structure for thermal stability.

The bus is a 2.12 m long hexagonal structure that is 0.94 m wide (Fig. 1). Electrical power is provided by a pair of deployable solar panels that provide >900 Watts when illuminated at near normal incidence. A pair of actuators is used to rotate these panels around the pitch (y) axis of the spacecraft bus to track the sun. The panels are used to charge a 35 Amp-hr nickel-hydrogen battery that provides power during eclipse. Redundant S-band receivers accept commands from the ground through helical omni-directional antennas. An S-band transmitter returns spacecraft and instrument housekeeping data to a ground station or through a Tracking and Data Relay Satellite (TDRS). Normally, both science and housekeeping data are returned to the ground station at 150 megabits/second using an X-band transmitter and a body-mounted X-band patch antenna. The command and data handling system manages the attitude control, power, propulsion, and telecom systems, and the 128 Gigabit solid-state recorder that stores the science data.

Figure 1 – Artist concept of Observatory over the Earth, showing the hexagonal structure, solar panels, and star tracker on the top of the bus. The Earth-pointing cylindrical structure protruding from the side of the bus just below the top is the baffle/calibration assembly for the instrument's telescope.

The spacecraft bus points the instrument for science data acquisition. It also points the body-mounted X-band antenna at the ground station for data downlink. The attitude control system uses 4 reaction wheels to control the pitch, roll, and yaw of the bus. A set of 3 magnetic torque rods is used to de-spin the reaction wheels. A star tracker, inertial measurement unit, and a magnetometer provide pointing information. A GPS receiver provides positional information along the orbit.

The hydrazine mono-prop propulsion system carries 45 kg of fuel to raise the orbit from the injection altitude (~635 km) to the operational orbit (705 km), adjust the orbit inclination as necessary, maintain the orbit during its 2-year nominal lifetime, and then de-orbit the Observatory at the end of the mission. The current best estimate of the spacecraft bus dry mass is ~315 ± 1 kg. The current best estimate of the observatory wet mass is 460 ± 1 kg.

Instrument

The instrument incorporates three, co-boresighted, long-slit, imaging grating spectrometers.[5,6] The spectrometers are optimized for the O_2 A-band at 0.765 µm and the CO_2 bands at 1.61 and 2.06 µm. The 3 spectrometers use similar optical designs and are integrated into a common structure to improve system rigidity and thermal stability (Figs. 2, 3). The current best estimate of the instrument mass is ~150 kg, and its average power consumption is less than <165 Watts.

An f/1.8 Cassegrain telescope views the Earth through a port in the side of the spacecraft bus. The light captured by the telescope is then recollimated, and then distributed to the entrance slits of the three spectrometers through a set of relay optics, designed to ensure that all three channels view the same scene (Fig. 2). The relay optics for each spectrometer also includes a beam splitter and narrow-band filter designed to transmit only the spectral range needed by that channel. A polarizer is included in front of each spectrometer slit to reject light polarized in directions that would not be transmitted to the focal plane by the grating.

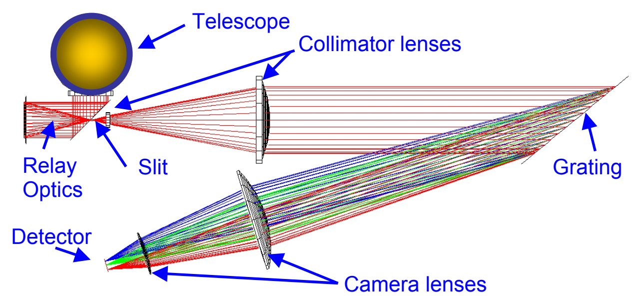

Figure 2 – Schematic of optical system layout for a single spectrometer, showing the entrance telescope, relay optics, slit, collimator, grating, camera and detector.

Once light passes through one of the 3 spectrometer slits, it is collimated by a pair of lenses, dispersed by a planar holographic diffraction grating, and then refocused onto a 2-dimensional focal plane array (FPA) with a 2-element refractive camera lens (Fig. 2). This optical system produces a 2-dimensional spectrum that captures wavelength variations in the direction perpendicular to the long axis of the slit and spatial variations in direction parallel to the long axis of the slit. This spectrum is imaged on a ~190 by 1024 pixel band across a 1024 by 1024 pixel FPA. The CO_2 channels use mercury cadmium telluride (HgCdTe) and O_2 A-band channel uses silicon as the photosensitive materials for their FPA's. Both the silicon and HgCdTe FPAs use the same read-out integrated circuit, simplifying the readout electronics. Each FPA is thermally isolated from the relatively warm (-5 °C) optical bench by cryogenic sub-system (CSS). The two CO_2 FPA's are cooled to −180 °C, while the O_2 FPA is cooled to −120 °C. Each FPA package includes a cold, narrow band filter designed to reduce the thermal emission and other sources of scattered light from within the body of the spectrometer.

In normal science operations, the instrument's three FPA's are each continuously read out at 3 Hz. To reduce the downlink data volume and increase the SNR, 20 adjacent pixels in the dimension parallel to the long axis of the slit (the spatial dimension) are summed on board to produce up to 8 spatially-averaged spectra. The along-slit angular field of view of each of these spatially-averaged “super-pixels: is ~1.8 mrad (~1.3 km at nadir from a 705 km orbit). The angular width of the narrow dimension of the slit is only 0.14 mrad, but the telescope focus was purposely softened to increase the effective full width at half maximum of each slit to ~0.6 mrad to simplify the boresight alignment among the 3 spectrometer slits. [6]

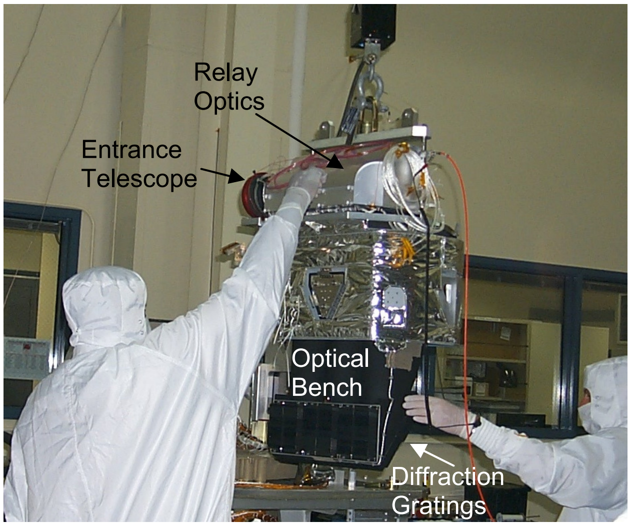

Figure 3 – Instrument primary optical assembly being hoisted into the instrument deck.

An on-board calibrator (OBC) is integrated into the telescope baffle assembly (Fig. 4). An actuator rotates a “propeller” that carries an aperture cover (lens cap) and a transmission diffuser. The cover is closed to protect the instrument aperture during launch and orbit maintenance activities. The cover is also closed to acquire “dark frames” that are used to monitor the zero-level offset of the FPAs. The inside of the cover has a diffusively reflecting gold surface that can be illuminated by one of 3 tungsten lamps installed the baffle assembly. These lamps are used to take “flat field” images that are used to monitor the relative gain of the individual pixels on the FPAs. The propeller is rotated 180 degrees from the closed position to place the transmission diffuser in front of the telescope aperture to view the sun. Measurements of direct sunlight through the diffuser provide an absolute radiometric calibration of the instrument and yield solar spectra for the full range of Doppler shifts (± ~7 km/sec) observed over the illuminated hemisphere. The propeller is rotated 90 degrees from either the closed or diffuser positions for normal science observations.

Operational Strategy

The bus points the instrument to collect science observations in Nadir, Glint, and Target modes [5]. In Nadir mode, the bus points the instrument aperture to the local nadir, so that data can be collected along the ground track just below the spacecraft. In Glint mode, the bus points the instrument aperture toward the bright “glint” spot. In Target mode, the bus points the instrument at stationary surface target as the observatory flies overhead.

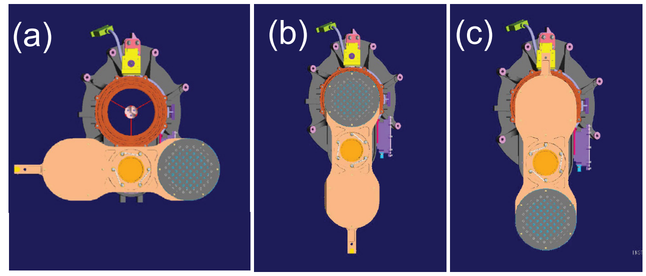

Figure 4: Telescope baffle assembly (a) open, (b) with solar calibration diffuser deployed, and (c) covered.

OCO will switch from Nadir to Glint observations on alternate 16-day global ground-track repeat cycles so that the entire Earth is mapped in each mode every 32 days. Comparisons between Nadir and Glint observations will provide opportunities to identify and correct for biases introduced by the viewing geometry. Target observations will be acquired over an OCO validation site roughly once each day. Solar, calibrations are acquired on every orbit as the spacecraft traverses the northern terminator, and goes into eclipse. Dark, and Lamp calibrations are collected while the observatory is in eclipse.

The instrument will collect 12 to 24 soundings every second while over the sunlit portion of the orbit, yielding 200 to 400 soundings per degree of latitude in the vicinity of the orbit track. These data will be downlinked to the NASA Ground Network Stations in Alaska and Virginia, and analyzed by the OCO Ground Data System at JPL.

5. Development Status

The OCO satellite bus and instrument being assembled and tested in preparation for environmental qualification testing. Once this process is complete, these two flight system parts will be integrated to produce the Observatory, and additional qualification testing will be performed.

Spacecraft Bus:

Spacecraft bus I&T work at Orbital Space Corporation (OSC) remains on schedule for completion in mid-January 2008 (Fig. 5). All of the components with the exception of the solar arrays and one of the 4 reaction wheels have been received at OSC and bus integration is underway. The recently integrated hardware includes the Three-Axis Magnetometer (TAM), X and Z Magnetic Torque Bars (MTBs), Body-mounted Coarse Sun Sensors (CSSs), Global Positioning System (GPS), Miniature Inertial Measurement Unit (MIMU), Solid State Recorder, X-band transmitter, S-band receiver & transmitter, Solar Array Drive Electronics (SADEs) and Solar Array Drive Assemblies (SADAs). The Solar Arrays and the fourth Reaction Wheel Assembly will arrive in November. These items will be integrated prior to bus comprehensive performance test (CPT), which is scheduled for November-December 2007. The bus will then go through its thermal vacuum test.

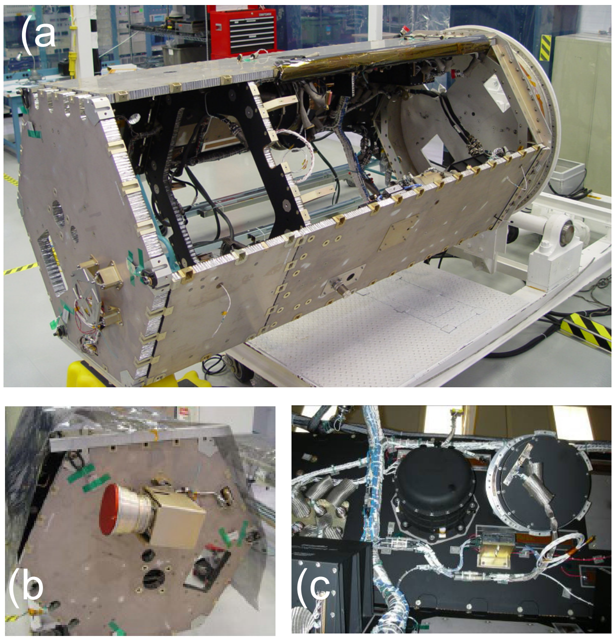

Figure 5: (a) The spacecraft bus structure early in the integration process. (b) The star tracker integrated on the top of the bus. (c) Bus subsystems including the inertial measurement unit and a reaction wheel.

Instrument:

The OCO 3 band spectrometer is currently being assembled and tested at JPL. A key milestone was met in the August-September time frame when the three focal planes were successfully focused and bonded into position. Since this process requires that the instrument and focal planes be at the operating temperature (180°C for the A-Band, 120°C for the two CO_2 channels), and the refractive optics were designed to focus in vacuum, it was necessary to put the spectrometer into a thermal vacuum (TV) chamber to determine the focus. To minimize the number of transitions from the TV chamber to ambient, a series of 9 small, precision, vacuum qualified piezoelectric motors (3 for each channel) were used to adjust the position (piston, tip and tilt) of the three FPA's (integrated into their cryo-subsystem) with respect to the optical bench. A laser metrology system provided an independent measurement of the FPA position throughout the focus process.

While in the TV chamber, the focus motors were used to move the FPA's through a range of positions while the instrument was illuminated with an external collimated light source. The light source was a tunable diode laser, but that produced a single spectral line on each FPA that was much narrower than the full width at half maximum (FWHM) of the instrument line shape function (ILS). The position of best focus was determined by minimizing the displacement of the laser line on the FPA as the instrument pupil was partially obscured (pupil-slicing) and by minimizing the measured FWHM of the ILS. Though problems were encountered using the focus motors, the process successfully established the focus in two of the channels, and the pupil slicing process verified that adequate focus had been achieved. The third channel required use of the pupil slicing to estimate the focus. The instrument was removed from the TV chamber, the focus motors were removed, and the FPA assemblies were hard-mounted to the optical bench using shims to maintain the focus position. The instrument was then reinstalled in the TV chamber and adequate focus was verified for all three channels. The instrument was then removed from the TV chamber and the final pinning (bonding) of the focal planes was performed.

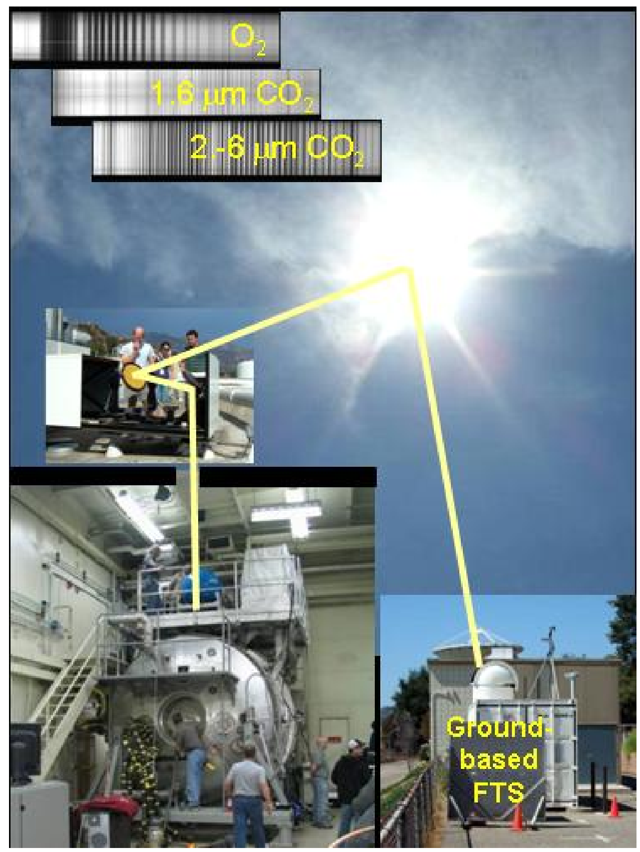

Figure 6 – Schematic illustration of the approach used to acquire simultaneous observations of CO_2 and O_2 in the Earth's atmosphere with the flight instrument (left) and a Fourier transform spectrometer during the first instrument thermo-vacuum test. The First-Light spectra from the flight instrument are shown at the top.

The primary intent of this first series of TV cycles was simply to establish spectrometer focus. However, once the instrument was focused and operating at temperature, we were able to test the majority of the calibration ground support equipment needed for the instrument comprehensive performance tests and acquire a significant amount of additional data. We also achieved "first light" on the instrument by acquiring atmospheric CO_2 and O_2 spectra using a heliostat installed on the roof of the TV building. The flight instrument results were compared to results from a ground-based, Fourier transform spectrometer that is part of the OCO ground validation program (Fig. 6). Initial radiometric calibration was performed, by gathering data to establish the zero-level offset (Dark Bias), Gain and Gain linearity. Spectroscopic measurements were made including Spectral range, resolution, sampling and Instrument Line Shape (ILS). Geometric measurements included initial Bore-sight alignment.

8. Summary and Conclusions

The OCO instrument and spacecraft bus are well into their integration and test phase. The completed Observatory is scheduled for delivery to Vandenberg Air Force Base for integration with the launch vehicle in early October 2008, in preparation for a launch in December of that year.

9. Acknowledgements

This work was performed by the Jet Propulsion Laboratory of the California Institute of Technology, under contract to the National Aeronautics and Space Administration.

References

[1] P.J. Rayner and D.M. O'Brien, The utility of remotely sensed CO_2 concentration data in surface source inversions, *Geophys. Res. Lett.* **28**, *175*, 2001.

[2] Warneke, T., Yang, Z., Olsen, S., Korner, S., Notholt, J, Toon, G. C., Velazco, V., Schulz, A. and Schrems, O., Seasonal and latitudinal variations of column averaged volume-mixing ratios of atmospheric CO_2. *Geophys. Res. Lett.*, 32, L03808, doi:10.1029/2004GL021597, 2005.

[3] Chevallier, F., Breon, F.-M., Rayner, P. J., Contribution of the Orbiting Carbon Observatory to the estimation of CO2 sources and sinks: Theoretical study in a variational data assimilation framework. J. Geophys. Res. 112 (D9): Art. No. D09307, 2007

[4] Baker, D. F., Doney, S. C., Schimel, D. S., Variational data assimilation for atmospheric CO_2. TELLUS Series B-Chem. And Phys. Met., 58 (5): 359-365 NOV 2006.

[5] D. Crisp et. al., "The Orbiting Carbon Observatory (OCO) Mission," *Adv. Space. Res., 34 (4),* 700-709, (2004) [doi:10.1016/j.asr.2003.08.062]

[6] R. Haring, R. Pollock, B. M. Sutin, and D. Crisp, "The Orbiting Carbon Observatory instrument optical design," *Proc. SPIE*, 5523, 51-62, Current Developments in Lens Design and Optical Engineering V; Pantazis Z. Mouroulis, Warren J. Smith, R. Barry Johnson; Eds. (2004).

Biography

Thomas R. Livermore is the project manager of the OCO mission. He has more than 20 years experience at JPL managing projects as diverse as the Cassini Image Science Subsystem, the Space Interferometry Mission, the Integrated Multispectral Atmospheric Sounder, the Multi-angle Imaging Spectro Radiometer, and the CloudSat mission before joining OCO.

David Crisp is a Senior Research Scientist at JPL and the Principal Investigator of the OCO mission. Over the past 21 years at JPL, Dr. Crisp has worked on a variety of flight projects, including the Hubble Space Telescope Wide Field Planetary Camera 2, Mars Pathfinder Lander, Mars Polar Lander, and Venus Express. He also served as the Chief Scientist of the NASA New Millennium Program from 1998 – 2001.